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14. ABSTRACT
Recent development in military and civilian applications requires switchable or tunable radar absorbers, which are very useful in electromagnetic compatibility test facilities, radar camouflage and deception roles, and tagging and asset tracking systems. There are a number of designs for tunable or switchable absorbers available in the literature. Almost all the designs use either liquid crystal materials or diodes to realize the tunability. Unfortunately, the operation bandwidth of most existing tunable absorbers is narrow and the achieved tunable frequency range is very small. Unlike existing tunable absorbers, we realize the tunable absorber through electronically changing its equivalent thickness of the absorber for different frequency bands. The operating principle is verified by theoretical analysis and experiment results. Both simulated and measured results show that this absorber can realize a wide bandwidth and its thickness is less than one-tenth free-space wavelength at the lowest frequency.

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1. Introduction

This report documents the research work conducted in the past one year (April 2011 to April 2012) for the project "Design of Tunable, Thin and Wide-band Microwave Absorbers" (Grant No.: FA2386-11-1-4048). It contains the following sections:

- Section 2 describes the design of a switchable microwave absorber. Its operating principle and detailed structure are explained. Simulated and measured results are also provided and compared.
- Section 3 presents the design of a dual-polarized switchable absorber. The absorbing structure is insensitive to the polarization of the incident wave due to its symmetry. Again, measured results are compared with simulated ones to verify the design concept.
- Section 4 introduces a design of wide-band microwave absorber using Vivaldi antenna array. Following the design of a wide-band array antenna, a tapered slot structure terminated with a resistor is used as a unit cell to implement a wide-band absorber. Simulation results are presented to demonstrate that the absorber can achieve a very wide bandwidth from 2.1GHz to 19.6GHz.
- Section 5 summarizes the work conducted and also highlights further works to be conducted in the next one year. Publications resulted from the project work are also included at the end of the report.

2. Design of a Switchable Microwave Absorber

The simplest absorber is probably the Salisbury screen, in which a thin resistive sheet is placed at a distance of $\lambda/4$ above a conducting plate. Recent development in military and civilian applications requires switchable or tunable radar absorbers, which are very useful in electromagnetic compatibility test facilities, radar camouflage and deception roles, and tagging and asset tracking systems.

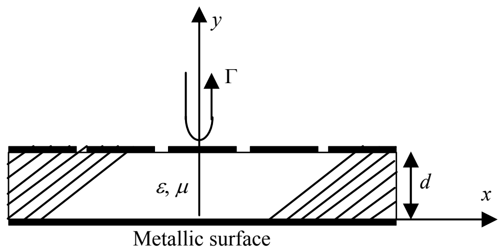
There are a number of designs for tunable or switchable absorbers available in the literature. Almost all the designs use either liquid crystal materials or diodes to realize the tunability. Unfortunately, the operation bandwidth of most existing tunable absorbers is narrow and the achieved tunable frequency range is very small. Unlike existing tunable absorbers, we realize the tunable absorber through electronically changing its equivalent thickness of the absorber for different frequency bands. The operating principle is verified by theoretical analysis and experiment results. Both simulated and measured results show that this absorber can realize a wide bandwidth and its thickness is less than one-tenth free-space wavelength at the lowest frequency.

2.1 The Absorption Principle

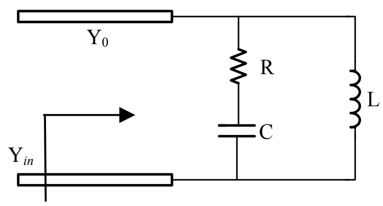
Fig. 1 shows a single-layer absorbing screen with a series capacitive circuit for impedance matching. It is known that this type of absorber can realize wide bandwidth with a relatively small thickness. Based on the equivalent circuit model, the input admittance Y_{in} is

$$Y_{in} = \frac{\omega^2 C^2 R}{1+\omega^2 C^2 R^2} + j\left(\frac{\omega C}{1+\omega^2 C^2 R^2} - Y\cot\beta d\right) \tag{1}$$

wher $Y = 1/Z = \sqrt{\varepsilon/\mu}$, $\beta = \omega\sqrt{\mu\varepsilon}$. , ε and μ are the permittivity and permeability of the substrate material, respectively.



(a) A single-layer capacitive absorbing screen



(b) Equivalent circuit

Fig. 1. A single-layer capacitive sheet separated from a metallic surface by a dielectric slab and its equivalent circuit.

When the thickness of the substrate is very small, for example, much shorter than a quarter wavelengths, the short-circuited transmission line shown in Fig. 1(a) can be represented by an inductor L. From the equation

$$j\omega L = jZ\tan(\beta d), \tag{2}$$

one can readily know

$$L = \mu d. \tag{3}$$

The reflection coefficient at the input port is then expressed as:

$$\Gamma = \frac{Y_0 - Y_{in}}{Y_0 + Y_{in}}. \tag{4}$$

Substituting (1), (3) into (4), we obtain

$$|\Gamma|^2 = \frac{\left(Y_0 - \frac{RC}{\mu d}\right)^2 + \left(\omega Y_0 RC - \omega C + \frac{1}{\omega\mu d}\right)^2}{\left(Y_0 + \frac{RC}{\mu d}\right)^2 + \left(\omega Y_0 RC + \omega C - \frac{1}{\omega\mu d}\right)^2} = M^2 \tag{5}$$

where M is the prescribed level of the reflection coefficient. (5) can be simplified as

$$a^2\omega^2 - p + \frac{1}{\omega^2\mu^2 d^2 C^2} = 0 \tag{5}$$

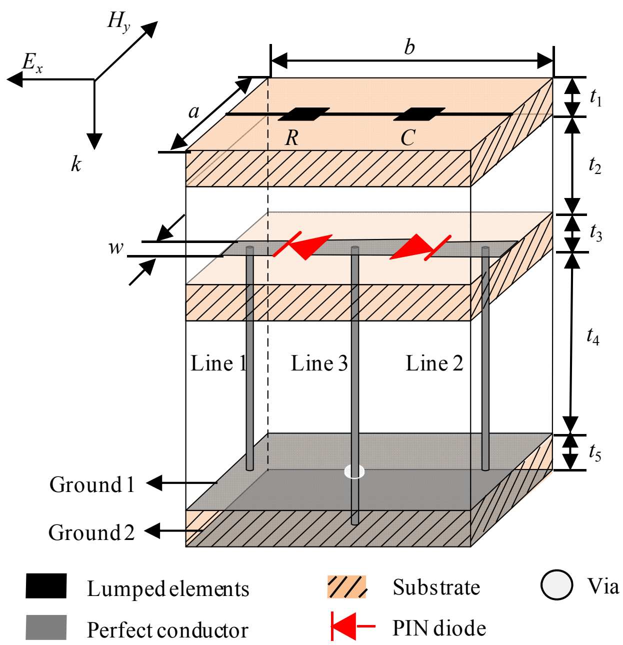
where $a^2 = Y_0^2 R^2 + 1 - 2Y_0 R\frac{1+M^2}{1-M^2}$, $p = \frac{2}{\mu dC} - \frac{R^2}{\mu^2 d^2} - \frac{Y_0^2}{C^2}$. If $a^2 > 0$, we can readily find from (6) that the central operation frequency is

$$\omega_0 = \frac{1}{\sqrt{(1 - Y_0 R)\,\mu d C}}, \tag{6}$$

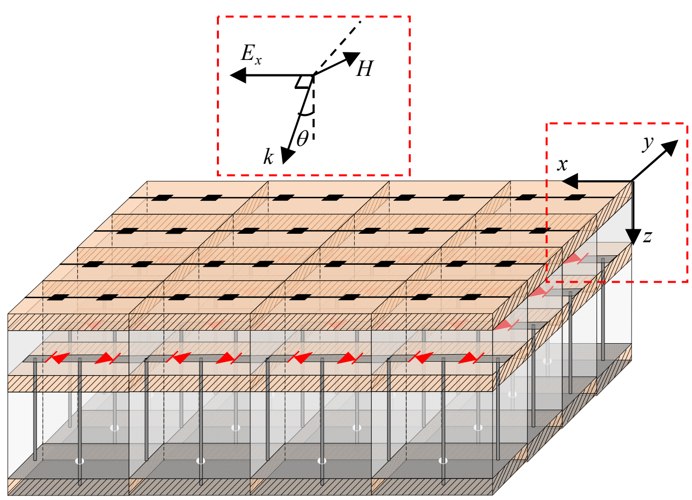
and the bandwidth of the absorber is

$$\Delta\omega = \sqrt{\frac{p}{a^2} - \frac{2}{a \mu d C}}. \tag{7}$$

It is obvious from (7) and (8) that, when other parameters are kept fixed, changing the absorber thickness d will result in different central frequencies and bandwidths. Based on this observation, we can design a new type of microwave absorber with switchable operation states by controlling the absorber's effective thickness.



(a) One unit cell



(b) 4 × 4 array

Fig. 2. Geometry of the proposed absorber.

2.2 Description of the Absorbing Structure

The proposed microwave CA absorber is designed based on the operating principle described in the previous section. Fig. 2(a) shows the geometry of one unit cell of our absorber with a TE incident wave. There is an air gap between each substrate in order to simplify the fabrication processes and to reduce material cost. We employ two PIN diodes that are in series with three metallic strips in each unit. Conducting Line 1 and Line 2 act as the cathode bias circuits of the PIN diodes, which are short-circuited to Ground 1, while Line 3 acts as the anode bias terminal of the PIN diodes, which is connected to Ground 2. They are utilized to realize different bias conditions for the PIN diodes. Fig. 2(b) shows the geometry of a 4 × 4 array of the absorber under an oblique incidence (θ away from the z-axis).

When no voltage is applied across the two PIN diodes, the RF current will flow on Ground 1, since the introduced PIN diodes are under the open state and no signals can pass through them. Under this condition, the proposed absorber can be deemed as a single-layer microwave CA absorber with a thickness of d_2 ($d_2 = t_1 + t_2 + t_3 + t_4$). On the other hand, when the PIN diodes are forward biased, i.e. Ground 2 is connected to the anode of an external voltage source, while Ground 1 is connected to the cathode of the source, the two PIN diodes are nearly short-circuit and RF signals can pass through them. The effective thickness of the absorber d_{eff} is $d_1 < d_{eff} < d_2$ under this biasing condition ($d_1 = t_1 + t_2$) since not all the RF signals flow through the PIN diodes. Therefore, by controlling the bias condition of the PIN diodes we can control the RF signal path and realize a new microwave CA absorber with two switchable operation states.

2.3 Simulated and Measured Results

In order to verify the design principle, we design and fabricate a microwave CA absorber shown in Fig. 3. The substrate material is RO 4230 (ε_r = 3.0). The structure parameters for each unit cell are as: a = 15mm, b = 15mm, $t_1 = t_3 = t_5$ = 1.524 mm, t_2 = 12 mm, t_4 = 18 mm. The values of lumped elements are R = 249 Ω, and C = 0.7 pF. The fabricated structure is 28.5 cm × 28.5cm, and comprises 19 × 19 unit cells. The PIN diode employed in the design is SMP1345-079LF type surface mountable PIN diode.

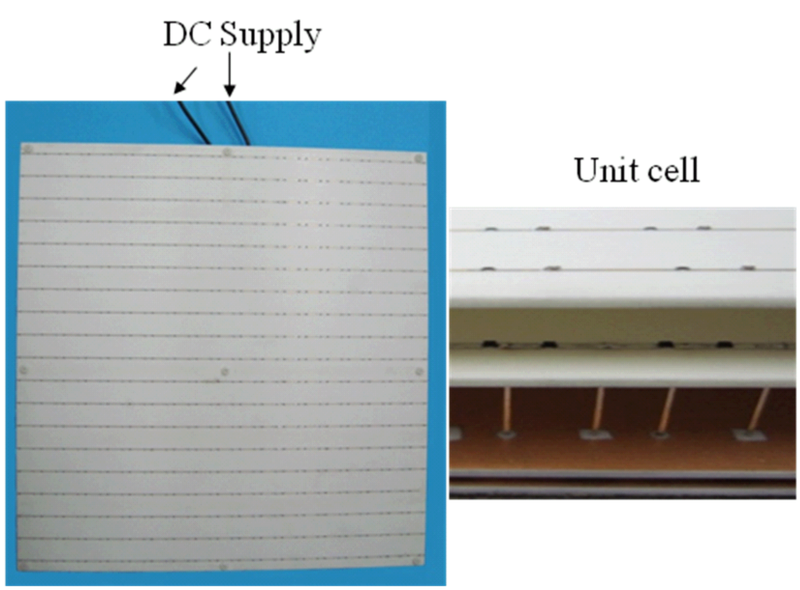


Fig. 3. Photo of the fabricated microwave CA absorber.

Measured results for the RCS reduction of the fabricated absorber under normal TE incidence are shown in Fig. 4. When no bias voltage is applied across the PIN diodes, the absorber operates within a frequency range of 0.85 GHz to 1.88 GHz with at least-10 dB reflection coefficient, narrower than the simulated bandwidth (0.88 GHz to 2.67GHz). When the forward current on each diode is about 10mA, the -10 dB reflectivity frequency band of the absorber switched to 2.66 GHz to 5.23 GHz, which is in good agreement with simulated one. The main reason of discrepancy between simulated and measured results for the first state is due to the small size of the fabricated absorber (1.7λ at 1.8 GHz) and the more significant diffracted fields from the edges at low frequencies, while simulation assumes an infinite array of unit cells. It is also known that the parasitic effects of the lumped elements and diodes may also contribute to the discrepancy.

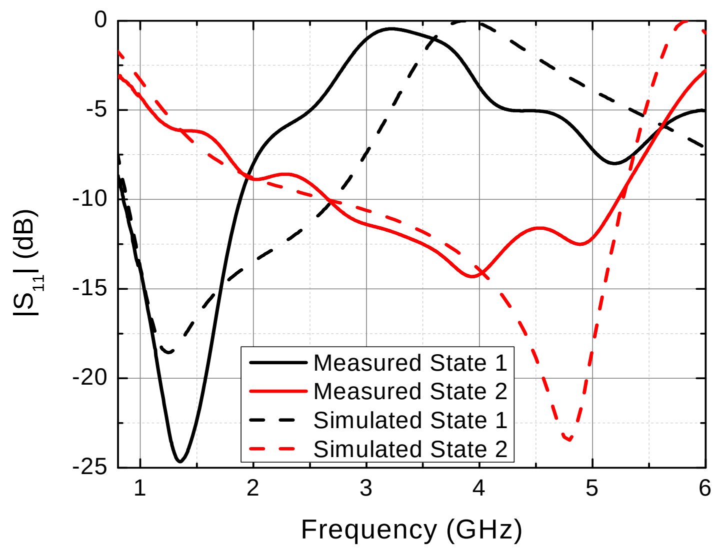


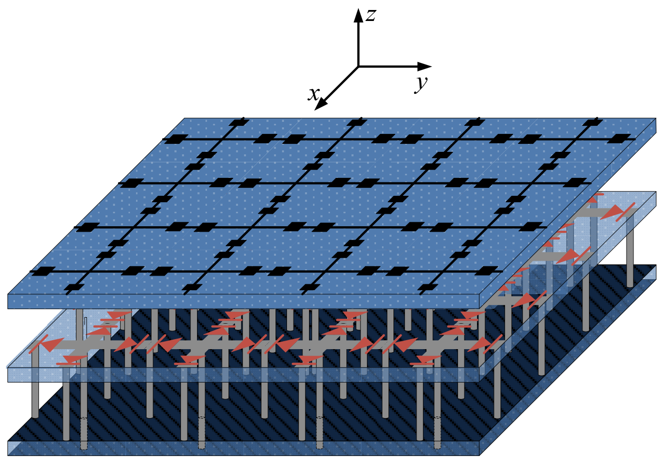
Fig. 4. Simulated and measured results of the proposed absorber.

In conclusion, we have proposed a new microwave CA absorber with two switchable states. Measured results have indicated that the -10 dB reflectivity frequency band of the proposed CA absorber can switch between 0.85 GHz to 1.88 GHz and 2.66 GHz to 5.23 GHz under normal TE incidence. Furthermore, the thickness is less than 10% of the free-space wavelength at the lowest operation frequency. In order to eliminate its dependence upon the polarization of the incident wave, a similar design for tunable dual-polarized microwave absorber will be presented in the next section.

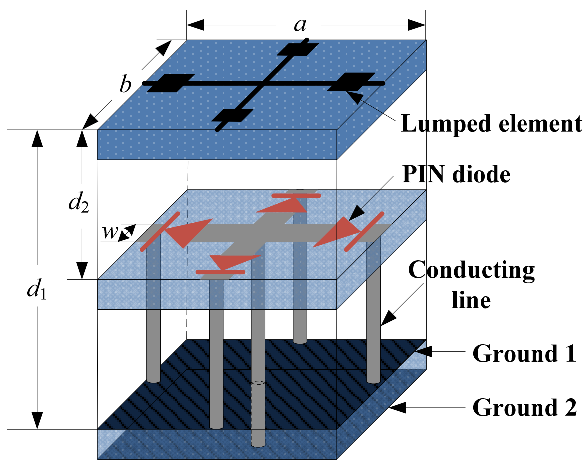
3. Design of a Dual-polarized Switchable Absorber

3.1 Description of the Absorbing Structure

As analyzed in the previous section, the thickness of the single-layer absorbing screen has a significant effect on the reflection coefficient due to its relationship with the equivalent inductor of the short-circuited transmission line. Our proposed dual-polarized switchable absorber is still based on this principle, while made symmetric. Fig. 5 (a) shows the geometry of the absorber, which is a two-dimensional periodic array of a three-layer structure: the top layer for the RC network, the middle layer for the PIN diodes, and the bottom layer for the ground plane. In each unit cell shown in Fig. 5(b), four conducting lines are connected to Ground 1, acting as the cathode bias circuits of the PIN diodes, whereas one conducting line is short-circuited to Ground 2, serving as the anode bias circuit. The incident electromagnetic waves are intercepted by the top capacitive sheet, which absorbs wave energy through suitable lumped circuit elements.



(a) 4×4 array



(b) One unit cell

Fig. 5. Geometry of the proposed dual-polarized circuit analog absorber.

When the PIN diodes are reverse-biased, they can be considered as infinite resistance, which prevent currents from flowing into them. Under this condition, the effective thickness of the absorber is d_1 and the absorber operates at the first state. When the PIN diodes are forward-biased, they are nearly short-circuited and currents will flow into them. Hence, the effective thickness of the absorber is d_2, and the second operating state can be achieved. Therefore, by switching the biasing condition of PIN diodes, we can simply change the current path and realize two tunable operating states. For a y-polarized TE incident wave, the series RC circuit along the y axis can control and absorbs the wave energy. Whereas for a y-polarized TM incidence, the series RC circuit along the x axis will be absorptive.

3.2 Simulated and Measured Results

In our design, the material of the top substrate and ground plane is RO 4003 ($\varepsilon_r = 3.44$) with a thickness of 0.813 mm, and the material of the PIN diode layer is RO 5880 ($\varepsilon_r = 2.20$), whose thickness is 3.175mm. As an initial guess, the effective thickness d_1 of the first state may be chosen as $\lambda/10$, where λ is the free-space wavelength at the lowest operating frequency. We keep d_1 = 11.99 mm since the starting frequency of the first-state operating band is 2.5 GHz.

Ansoft's high frequency structure simulator (HFSS) is employed to obtain simulated results for an infinite array of the proposed absorber using periodic boundary conditions, as shown in Fig. 6. It should be mentioned that the absorption performances for normal TE and TM incidences are almost the same due to its symmetric structure. The maximum bandwidth can be achieved by carefully choosing the dimensions of the structure and values of the lumped elements. Reducing R or increasing C can result in a broader bandwidth for the first state, but a narrower bandwidth for the second state.

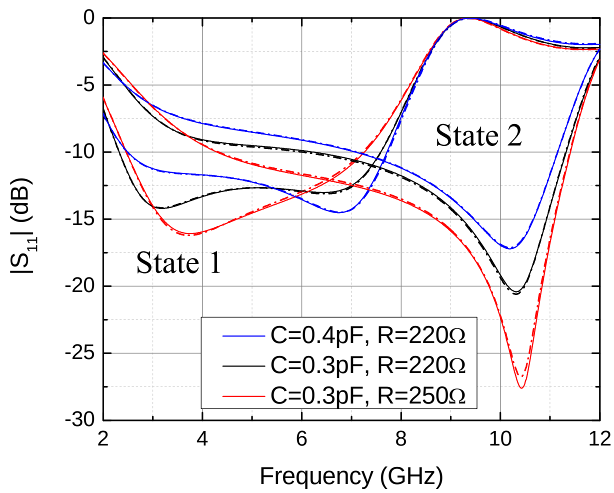


Fig.6. Simulated reflection coefficient of the absorber for various values of lumped elements under normal TE and TM incidences (a = 10 mm, b = 10 mm, d_1 = 11.988 mm, d_2 = 6.813 mm, w = 1.2 mm).

With appropriate parameters of the structure, the absorber operates within a frequency range of 2.4 GHz to 7.4 GHz for the first state with at least -10 dB reflection coefficient, and 4.4 GHz to 11.4 GHz for the second state under normal TE incidence, as shown in Fig. 7. This design is then fabricated and tested in an anechoic chamber. The parameters of the final design for each unit-cell are as: $a = b$=10 mm, d_1 = 11.988 mm, d_2 = 6.813 mm, w = 1.2 mm. The values of lumped elements are R = 240 **Ω**, and C = 0.3 pF. The fabricated structure is 13 cm × 13 cm, and comprises 13 × 13 unit-cells, as shown in Fig. 8. The PIN diode employed in the design is MA4SPS402 type surface mountable PIN diode. The forward current flowing on each PIN diode is 20mA.

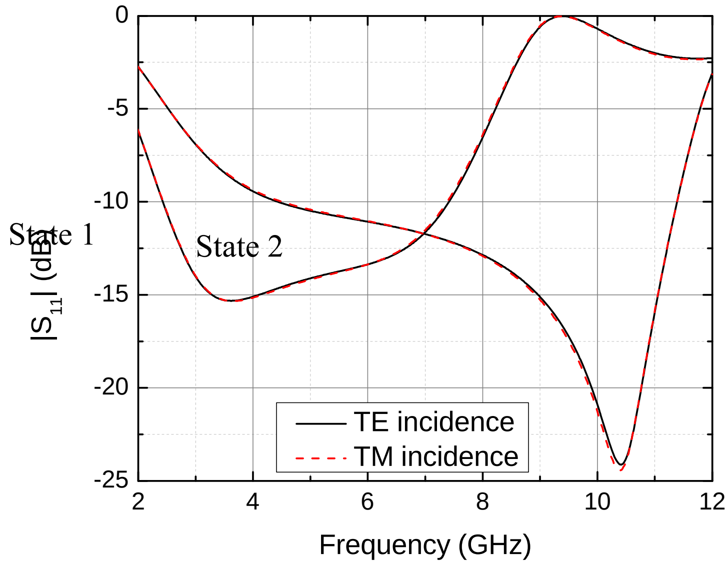
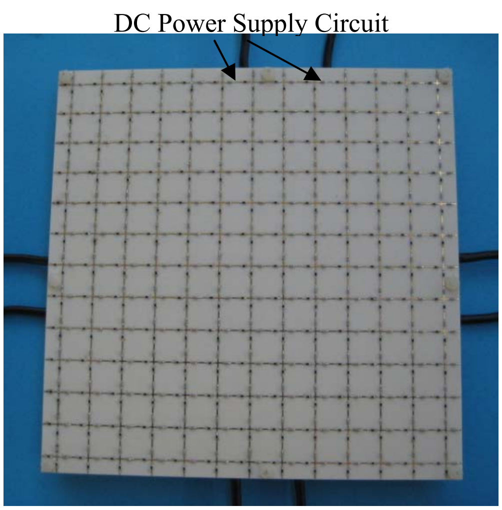
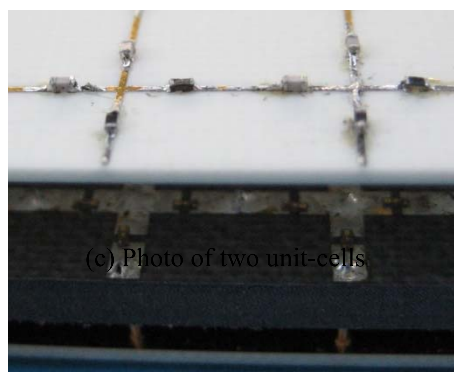


Fig. 7. Simulated reflection coefficient of our designed dual-polarized switchable absorber (a =b=10 mm, d_1 = 11.988 mm, d_2 = 6.813 mm, w = 1.2 mm, C = *0.3* pF, R = *240* Ω).



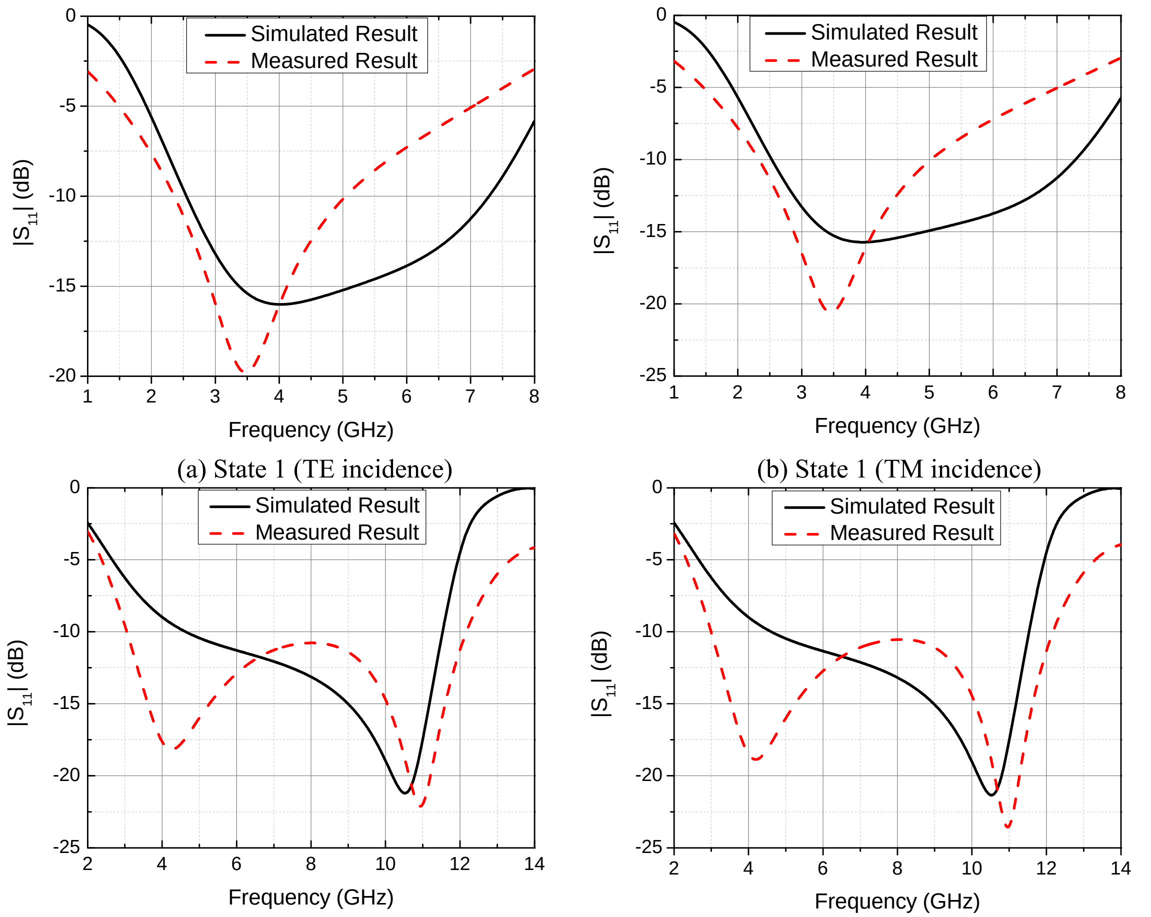
(a) Photo of the fabricated model



(b) Geometry of one unit-cell

Fig. 8. Photo of the fabricated dual-polarized switchable absorber.

Simulated and measured results for the RCS reduction under normal TE and TM incidence are shown in Fig. 9. When no bias voltage is applied across the PIN diodes, the absorber operates within a frequency range of 2.36 GHz to 5.05 GHz with at least-10 dB reflection coefficient, narrower than the simulated bandwidth (2.55 GHz to 7.28 GHz). When the PIN diodes are forward-biased, the -10 dB reflectivity frequency band of the absorber switched to 3.00 GHz to 12.18 GHz, wider than the simulated bandwidth (4.60 GHz to 11.54 GHz).



(a) State 1 (TE incidence)

(b) State 1 (TM incidence)

(c) State 2 (TE incidence)

(d) State 2 (TM incidence)

Fig. 9. Simulated and measured RCS reduction of the fabricated absorber.

The main reason of discrepancy between simulated and measured results for State 1 is due to the fact that the size of the absorber is only 2.1λ at the center frequency of 4.9 GHz, which cannot satisfy the requirement of infinite unit-cells, in addition to the fabrication error and the coarse soldering process for inserting the elements into the structure. There are two resonant frequencies for State 2, which should be attributed to the imperfect performance of the PIN diodes and the parasitic effect of the chip resistors and capacitors at high frequencies.

4. Design of a Wide-band Absorber Based on Vivaldi Antenna

In this section, we propose a novel concept to design wide-band microwave absorbers, which is to use wide-band antenna arrays terminated with matched loads. Fig. 10 shows the geometry of a wide-band absorber employing the wide-band Vivaldi antenna array. Each Vivaldi element is terminated with a resistor. The unit-cell of the absorbing structure is shown in Fig. 11. The exponential tapering coefficient p of each structure is 0.1mm^{-1}. Each unit cell consists of two substrates for widening the operating bandwidth due to its multiple resonances property. The first substrate has a dielectric constant ε_{r1} =6 and a thickness of 0.3mm, while the second substrate has a dielectric constant ε_{r2} =4.4 and a thickness of 0.3mm. Other parameters are as follows: L_1=30 mm, Rs_1=3 mm, R_1=80 Ω, L_2=28 mm, Rs_2=2.5 mm, R_2=120 Ω, d=8.04 mm, $2y_0$=0.4 mm, x_0=36.5 mm. Simulated reflectivity of the Vivaldi absorber is shown in Fig. 12. It can be seen that the bandwidth is 2.1GHz to 19.6GHz, which is very wide. It should also be mentioned that the design can be readily made as a dual-polarized one, just like the dual-polarized Vivaldi antenna array.

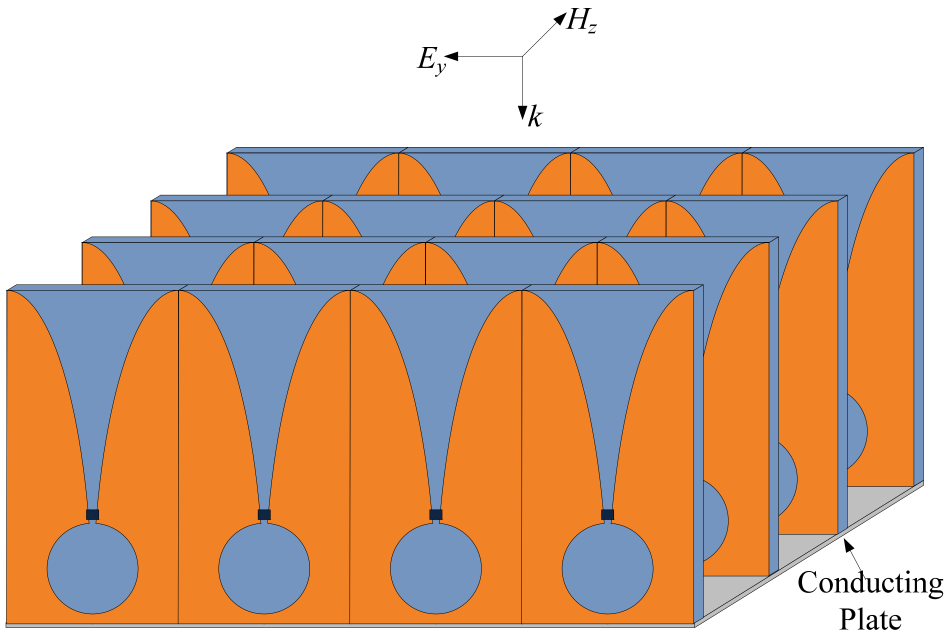


Fig. 10. Geometry of a wide-band microwave absorber using Vivaldi array.

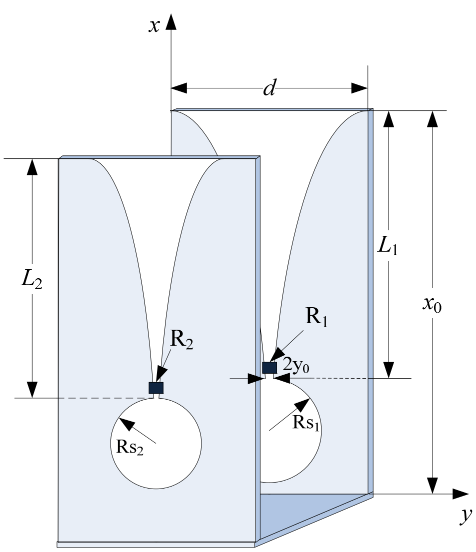


Fig. 11. Geometry of the unit cell.

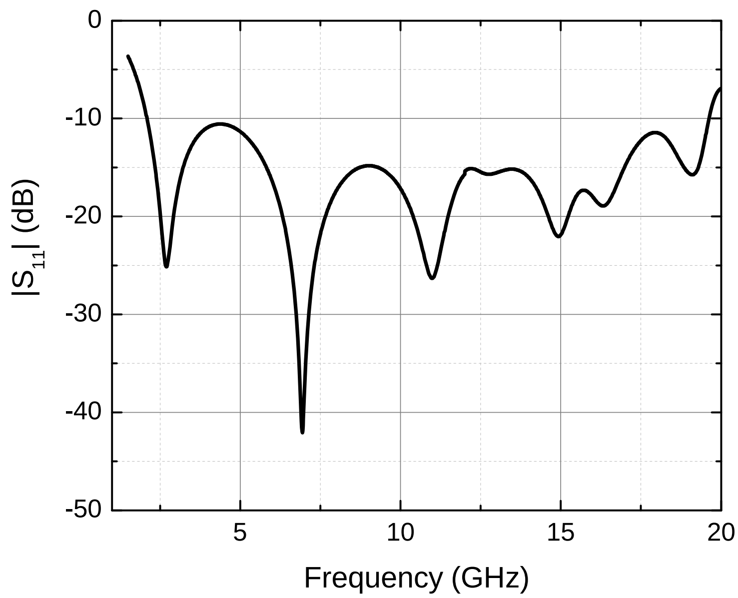


Fig. 2. Simulated reflection coefficient of the proposed wide-band Vivaldi absorber.

It should be mentioned that although this microwave absorber employing Vivaldi elements exhibits a very wide frequency band, its profile is relatively thick compared to the planar structures. This is due to the tapering structure introduced to excite the traveling waves for a wide bandwidth. In the meanwhile, we also tried to insertion a thin layer of magnetic material to reduce its thickness. However, it turns out that inserting a thin magnetic layer is not very effective in reducing the Vivaldi antenna height because the length of the tapering section determines the number of multiple resonances, while the conductor-backed magnetic slab produces a reactance that is changing with the frequency. However, this preliminary study has resulted in a more promising structure to realizing thin and wide-band microwave absorbers, which will be briefly described in the next section as future work.

5. Recommendations for Further Work

In the past one year, we have conducted extensive research on the design of switchable microwave absorber. Emphasis has been laid on the concept proof by experimental measurements. A new concept for the design of wide-band microwave absorbers using Vivaldi array has also been explored and simulation results have demonstrated its feasibility though much work is needed to reduce its thickness.

In view of the work conducted, we envisage the following work worthwhile to pursue further in the next one year.

(a) The thickness of our designed wide-band Vivaldi absorber may be reduced to suit practical applications. Some considerations on this issue have led to the usage of other low-profile wide-band antenna structures. One of the promising structures is the planar spiral antenna, which may be employed for our thin and wide-band absorber design. The most challenging issue with the design of a low-profile wide-band spiral antenna is the implementation of the thin reflecting ground because the thin ground below the spiral antenna will make the antenna inefficient and narrow-banded in the lower frequencies. In order to achieve a wide-band performance and low-profile structure, we plan to explore a tapered electromagnetic band-gap (EBG) structure to realize a frequency-independent reflecting ground so that a low-profile and frequency-independent spiral antenna terminated with a matched load can be obtained as the thin and wide-band absorber.

(b) Inspired by the multiple resonances appearing in the Vivaldi absorber, we also hope to explore a new structure that may also be promising for thin and wide-band absorbers. The new structure consists of a two-dimensional periodic array of unit cells and each cell contains multiple square loops printed on a substrate. Resistors can be inserted into the square loops to make it a resistive frequency-selective surface, which is then placed at a small distance above the conductor-backed EBG structure that is similar to the one used in the spiral absorber. This structure may become another promising structure that deserves careful investigation.

It should be pointed out that other wide-band antenna structures or other ideas may also be explored for realizing thin and wide-band absorber in the next one year.

6. Publications in the Past One Year

[1] Q. Zhang, Z. Shen, J. Wang and K. S. Lee, "Design of a switchable microwave absorber," Resubmitted with minor revision to *IEEE Antennas and Wireless Propagation Letters*, 2012.

[2] Q. Zhang and Z. Shen, “A dual-polarized switchable microwave absorber,” IEEE AP-S International Symposium, Chicago, July 2012.